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MIPR NUMBER 96MM6721

TITLE: Contrast Enhancement of Mammograms By Optical Polarization of the Viewing Environment

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CONTRACTING ORGANIZATION: U.S. Food and Drug Administration
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REPORT DATE: June 1997

TYPE OF REPORT: Annual

PREPARED FOR: Commander
U.S. Army Medical Research and Materiel Command
Fort Detrick, Frederick, Maryland 21702-5012

19970910 063

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	June 1997	Annual (15 May 96 - 14 May 97)

4. TITLE AND SUBTITLE
Contrast Enhancement of Mammograms By Optical Polarization of the Viewing Environment

5. FUNDING NUMBERS
96MM6721

6. AUTHOR(S)
David C. Spelic, Ph.D.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Food and Drug Administration
Laurel, Maryland 20708

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Commander
U.S. Army Medical Research and Materiel Command
Fort Detrick, Frederick, Maryland 21702-5012

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200*

Purpose: To investigate the optical polarimetric properties of mammography films and determine whether visual contrast may be improved by exploiting such properties with a suitable viewing environment.

Scope: The major efforts of the first year of this investigation have concentrated on experimental design and procedure development, preliminary studies of a selected mammography film type for prominent polarimetric properties, and data analysis procedures for Mueller matrix analysis.

Major findings: Preliminary analysis of the mammography film selected shows that there are definite polarimetric properties displayed by the film. A subtle effect on the observed linear polarization due to film optical density variations warrants further, more rigorous study than that completed thus far. It was also found that the film's plastic base itself displays prominent retardance which will need to be considered when isolating potential candidates for further testing.

14. SUBJECT TERMS Breast Cancer mammography contrast x-ray polarization optics

DTIC QUALITY INSPECTED 4

15. NUMBER OF PAGES
18

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unlimited

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Introduction

The goal of this project is to investigate the potential polarimetric properties of mammographic films and to characterize any observed properties in terms of their possible exploitation for the improvement of observed contrast. Currently mammographic films are viewed using simple optical light sources such as the view box and the hotlight. These devices are incapable of rendering visible any potential polarimetric properties displayed by the mammograms. A possible spin-off from the project would thus be a viewing environment that would exploit polarimetric properties and allow the user to adjust the perceived mammogram.

The nature of any observed polarimetric properties may originate from either the film base itself- the material which merely serves as a support surface for the image- or could originate from the actual film emulsion- that material responsible for the production of images. The film emulsion consists of crystal grains of various sorts which, when exposed to radiation forms a latent image- that is, a reconfiguration within the crystals with a distribution on the film base representative of the mammographic image, but as yet invisible to the eye. The mammogram is then developed, during which the latent image is rendered visible. It is our hope that we may observe polarimetric properties which are linked to the level of optical density on the mammographic film (i.e. the degree of darkening on the film).

Thus far efforts have concentrated on one particular brand and type of film, Eastman Kodak's Min R E film. This would allow us to configure and optimize experimental procedures for evaluating other types of films. We currently expect to evaluate all types/brands of mammography film commercially available, as well as possibly some older films which may no longer be easily available, but which have unique structural features that may display potential polarimetric properties of interest and value.

Experimental designs for the entire project were broken down into two levels of study: feasibility studies and comprehensive studies. Feasibility studies would be conducted in order to determine whether prominent polarimetric properties existed, whether there was a dependence on any observed properties on film optical density. Comprehensive studies would focus on detailed analysis of any displayed polarimetric behavior, including spectral dependence of such behavior. It is also important to determine to what extent the film base contributed to any observed polarimetric phenomena. If observed behavior were linked to the film base as well as to the emulsion, then further, more rigorous experimentation would have to be conducted. The following describes the experimental set-up, procedure and results of experiments we have completed or initiated thus far.

Feasibility studies

Experiment I.

1. Purpose: To quantify the linear dynamic response of optical detector

2. Experimental Set-up: The performance of the acquired photodetector and amplifier were evaluated by determining the system's dynamic range of linearity. A photodetector (Newport, model 818-UV) was used in conjunction with a large dynamic range photodetector amplifier (Melles Griot, model 13 AMP 003) to measure output light intensity. Neutral density filters were used to reduce the intensity levels incident on the detector. A plot of the detector's response is shown below in figure 1. The x-axis displays optical density, which is defined as,

$$\text{Optical Density} = \log\left(\frac{\text{Incident Intensity}}{\text{Transmitted Intensity}}\right)$$

From the plot it can be seen that for the range of optical densities which will be investigated in this project, potentially up to 4.0, the detector response is quite linear. Error bars were not determined as it was important merely to determine that the detector responded in a linear fashion with optical density. It should be noted that the beam intensity which enters the detector is also dependent on the intensity of the source and also on the fraction of light transmitted by any analyzing (post-sample) optical components. Currently we are using a lamp of relatively low power output, approximately 50 watts. We have purchased lamps of 100 watt and 250 watt capability to handle not only the high optical densities of the film, but to also handle the inevitable decrease in intensity due to the optical elements in the experiment, namely the retarders and polarizers.

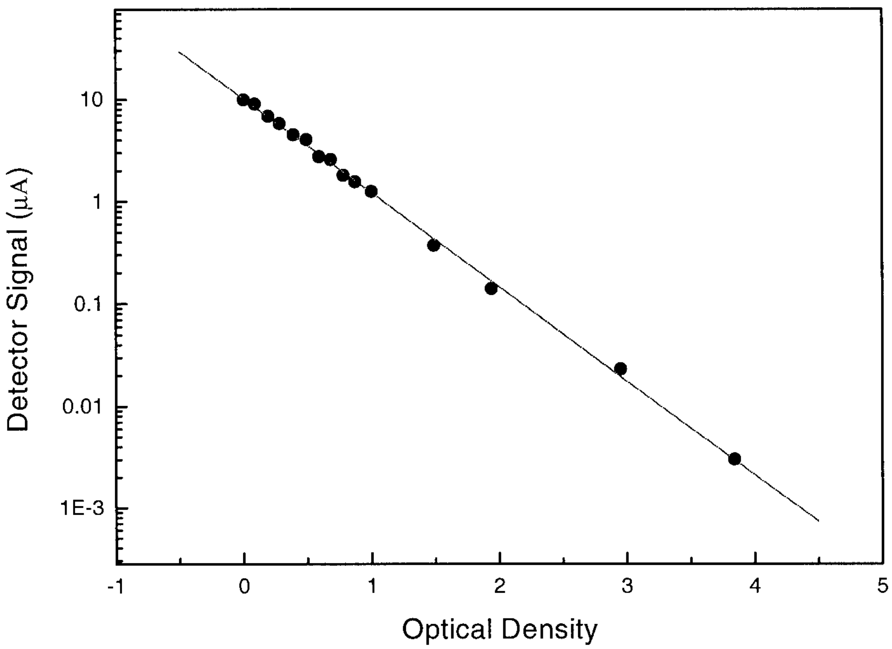

Figure 1. Plot of output from photodetector versus input optical density.

Experiment II.

1. Purpose: To investigate and measure the presence of prominent dichroism which may depend on the optical density of the film tested.

2. Experimental set-up.

Dichroism is the ability of a substance to selectively absorb radiation which has a component of electric field vibration in a certain orientation. More commonly known as polarizers, they can be either materials such as sheet polaroid, or devices which display the same behavior. Figure 2 below illustrates the experimental set-up for investigating prominent dichroic properties of mammographic films. In this experiment a film sample of a given optical density was positioned between two aligned polarizers (Glan-thompson polarizer, Melles Griot). The input light source used was tungsten-quartz halogen (Oriel), and optical detector specified above was used to obtain photometric measurements. At this time only one film brand/type, Eastman Kodak Min R E (Eastman Kodak, Rochester, NY) was investigated.

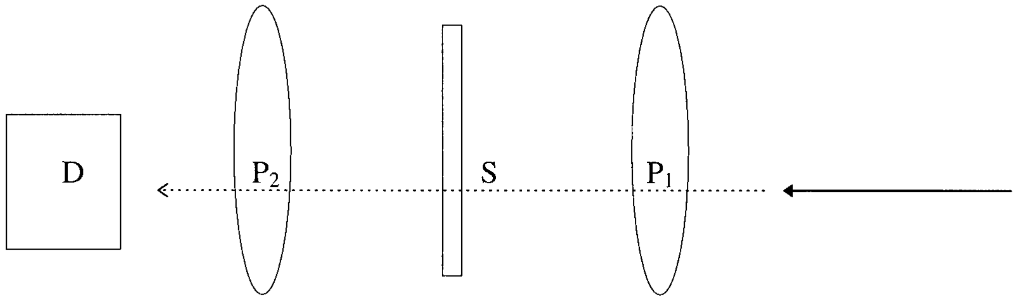

Figure 2. Optical set-up for experiment II.

3. Experimental procedure.

Polarizers P_1 and P_2 are aligned such that in the absence of any film sample S, maximum signal output is observed. A film sample S is subsequently placed between the two polarizers after which polarizer P_2 is then rotated and photometric measurements are taken. Ideally one would hope to observe polarimetric phenomena which would occur over a range of orientations of the film sample S with respect to polarizer P1, the first film sample was therefore placed within the set-up more or less randomly with respect to P1, as this is how mammograms would be viewed (a potential viewing device should not expect to rely on readers always positioning their film such that a certain preferred direction by the film is always aligned appropriately.) The light source (Quartz-Tungsten Halogen lamp) contains a broad spectrum covering the visible range of wavelengths. Care was taken to ensure that the orientation of each sample of film was consistent in order to rule out further effects due to relative film orientation with respect to P_1.

4. Results

Figure 3 below illustrates the experimental results for Min R E mammography film samples of indicated optical densities, and also for the case of no sample. Again, the purpose of this experiment was to determine the presence of any prominent polarimetric behavior with respect to levels of film optical density. As can be seen from the plot, there is a small shift in the profiles as film density increases. Thus there is a subtle dependence of the transmitted orientation of incident polarized light on the optical density of this particular sample of film. Since the trend is subtle, the results below were considered quite preliminary until the comprehensive determination of the polarimetric properties of the film could be completed.

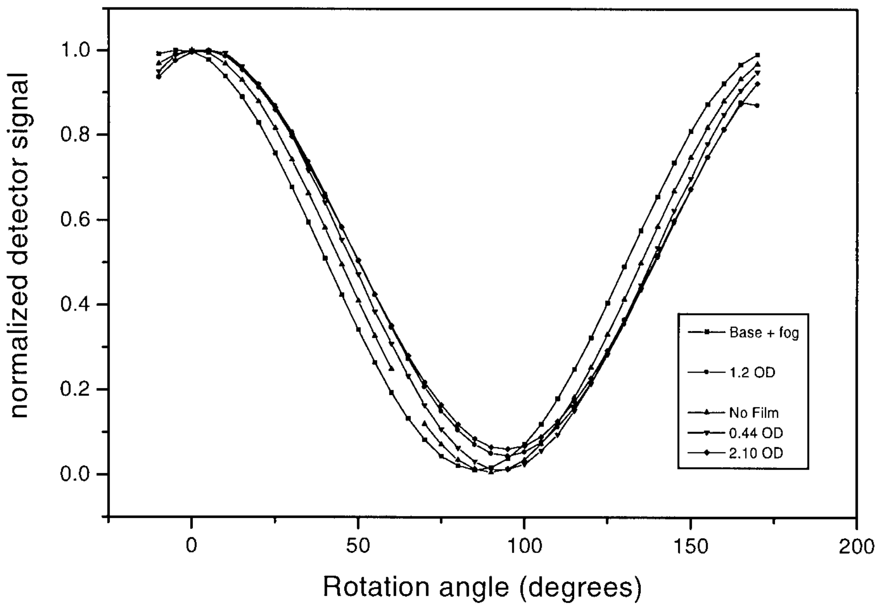

Figure 3. Plot of results from experiment II. Each curve has been normalized since the amplitude changes from a density level for the film of base+fog to a density level of 2.1 were substantial.

As little was known regarding the optical polarimetric properties of the film base itself, the first set of measurements was taken without regard to the orientation of the film. Hence prominent polarimetric features of the film base itself rendered invalid earlier sets of data when it was found that the base alone had these properties.

Experiment III.

1. Purpose: To investigate the potential bifringent properties of the film base for Kodak MinR E mammography film.

2. Experimental Set-up:

Light incident on a material which displays birefringence experiences a different refractive index depending on the orientation of the electric field vector with the optical axis of the material. Figure 4 illustrates the experimental set-up for investigating the extent to which the film base contributes to any observed birefringence by the film sample. The set-up is structurally identical to the experimental set-up for experiment II.

However, in this experiment, the film sample is rotated relative to the polarizers. This allows for orientation of the polarized light from P_1 to enter the sample at various angles. A preferred direction in the film base would be evident from this type of investigation since effectively the orientation of the light incident on the film sample is varied. In order to observe such behavior from only the film base, a sample of Kodak Min R E film with no initial exposure was developed, leaving just the base of the film itself.

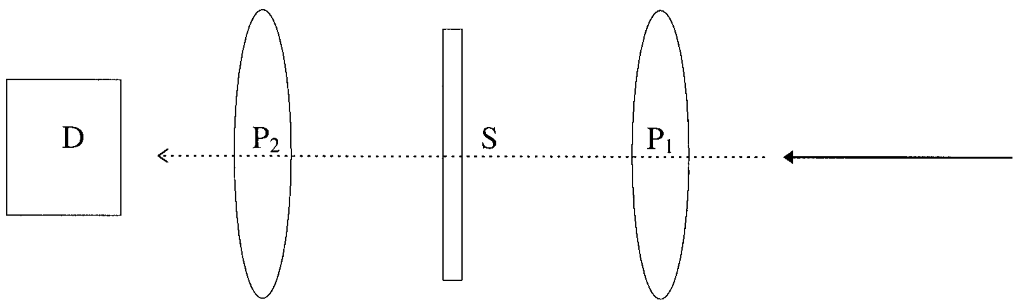

Figure 4. Illustration of set-up for experiment III.

3. Results

The results are shown in the figure 5 below. The behavior of the film base is primarily that of a quarter wave retarder, because as the sample is rotated to the point where the incident light is oriented at 45 degrees with respect to the fast axis of the film base, circularly polarized light results, as evident from the variation in the signal over a rotation of 45 degrees, from a minimum relative signal level of approximately 0.5 (no retardance, so the electric field vector oscillates between E_o and zero) to the peak signal level, when the beam is retarded, and the time average of the circular polarized light is twice that of the unretarded beam.

Out of interest, a sample of MinR E film at an optical density of 1.7 (a fairly typical clinical level of optical density) was also investigated to see if optical density influenced the degree of retardation. As shown by the curves below, there was a slight influence on retardance by an increase optical density.

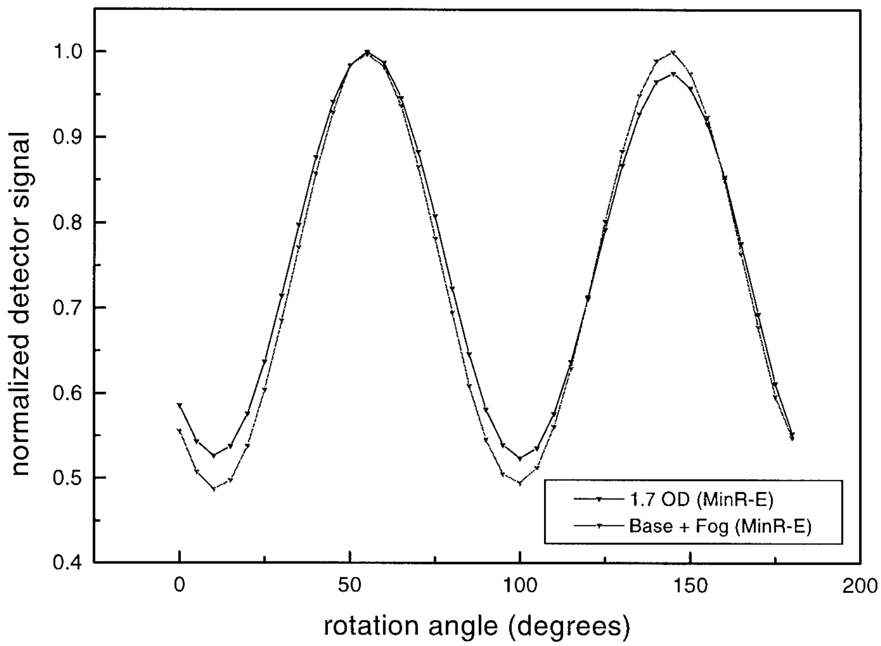

Figure 5. Plot of detector signal versus rotation of the film samples.

4. Discussion

As there is a strong retardance displayed by the film base for the film brand/type tested, more subtle polarimetric properties originating from the film emulsion may not be observable using the above experimental set-up. It is entirely possible that polarimetric phenomena which display a dependence on the film's optical density are observable only at certain discrete optical wavelengths or bandwidths, necessitating spectral measurements. Further investigations with other film brands and types will be conducted using the above experimental set-up.

Comprehensive studies

Experiment IV. Mueller matrix evaluation

1. Purpose: To develop experimental set-up and data analysis procedures for determining the Mueller matrix of mammography film samples.

In order to completely describe the optical polarimetric properties of mammographic films, an experimental set-up was configured which would allow determination of the Mueller matrix elements. The Mueller matrix formalism describes completely the polarimetric properties in a 4x4 matrix. In this methodology, light of a specific polarization state is treated as a 4x1 column vector, and the Mueller matrix transforms the polarization state of the input light vector,

$$[E'] = [M]\cdot[E]$$

where M is a 4x4 matrix containing all the information on the polarimetric properties of the material which the light is incident on, and E and E' are 4-element column vectors in which E is the incident polarization state, and E' is the subsequent polarization state. The determination of M is relatively straight-forward, but can be computationally intense depending on the quality of the optical elements used to make the necessary measurements.

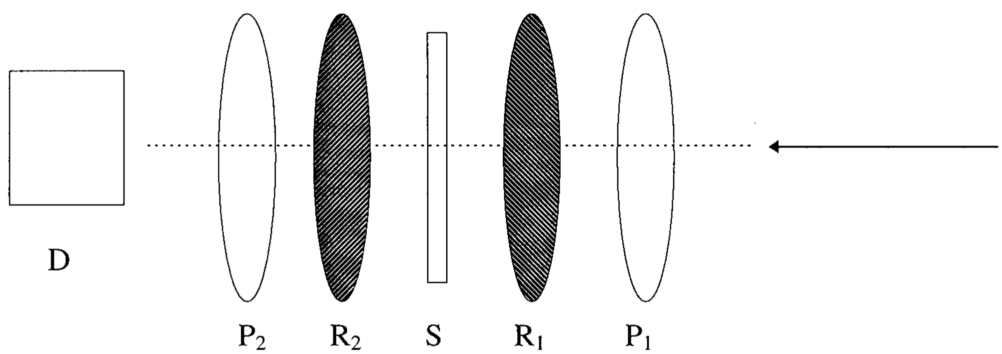

Figure 6. Set-up for measurements allowing Mueller matrix determination.

2. Experimental set-up and procedure

Figure 6 illustrates the configuration of the optical components utilized in the experiments. During this experiment polarizers P_1 and P_2 are aligned and quarter-wave retarders R_2 and R_1 (Achromatic retarder #AQM-200-0545, Medowlark Optics, Longmont, CO) are rotated. For each data point R_1 is rotated by a selected angle ϑ and R2 is rotated by 5ϑ., and the method of Azzam[1] is following in analyzing the data. For the data set below, $\vartheta = 5^{o.}$ In order to validate the experimental set-up and to develop and verify the procedures for data analysis, measurements were taken without a sample (air only) as for this case, the Mueller matrix should be the unity matrix.

3. Results

The plot in figure 7 below illustrates the photometric measurements taken on the configuration described above. At the time of preparation of this report, the data from the plot of figure 7 was still being analyzed. A commercial math software package, MathCad was used to perform a discrete Fourier transform (DFT) on the signal, however the values obtained did not provide acceptable results. We plan to repeat the experiment and are coding our own form of the DFT in order to verify the results provided by the commercial math software.

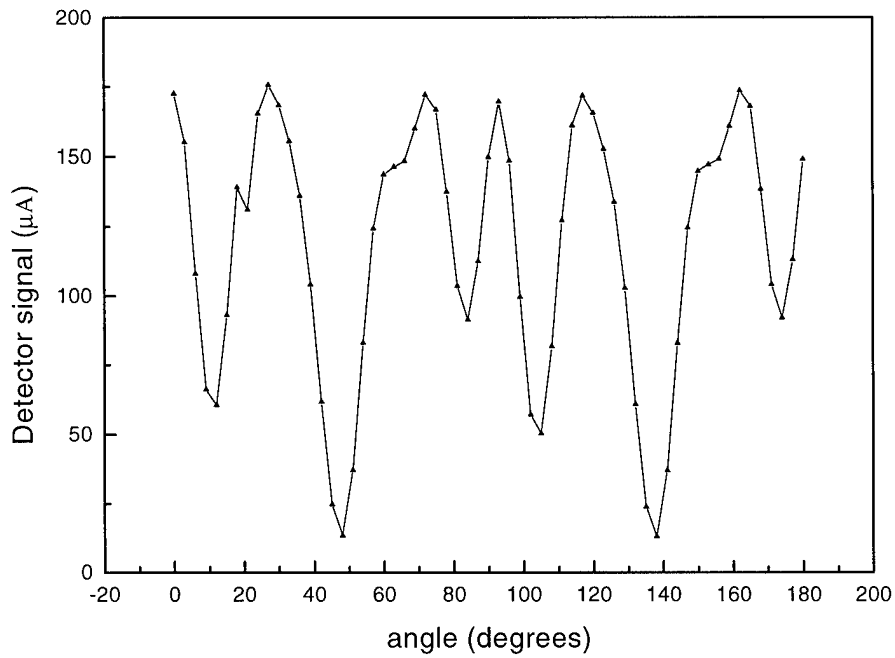

Figure 7. Plot of detector output versus rotation angle of retarder R_2 for experiment IV.

4. Discussion

We are currently in the process of validating the experimental set-up and data analysis procedures to be used in the determination the Mueller matrix coefficients. As the incident light source used for the measurements contained a broad spectrum over the visible range, slight variations in the degree of retardance can introduce anomalies. Also, there resulted optical phenomena caused by reflection from the surface of the film sample (discussed below). Finally, in the interest of testing the alignment and mechanics of the experimental set-up, proper optical isolation of the experimental apparatus including the modulation of the input light source and detection using lock-in amplifiers were not fully implemented. Use of a chopper to modulate the incident light source and detection by use of a lock-in amplifier will allow virtual elimination of contributions to the detected signal by any extraneous light sources.

Experiment V. Spectral measurements.

1. Purpose: To develop procedures for investigating spectral dependence of polarimetric properties for mammography film samples.

This aspect of the investigation is very preliminary, and the primary goal was to configure a spectrometer for making spectral measurements on the output signal from the experimental apparatus described in experiment IV above. There may exist discrete spectral frequencies or narrow bands at which there are strong polarimetric properties displayed by the film emulsion which are not obvious when evaluating the sample using broad spectral sources.

2. Experimental set-up and procedure

The configuration shown in figure 8 was used to measure optical spectra exiting the analyzing polarizer, P_2. Note that this configuration is identical to that of experiment IV above. The goal of this experiment is to ultimately be able to determine specific spectral values for which polarimetric behavior may be especially prominent with respect to the film emulsion. A CCD-based spectrometer was configured to obtain spectral measurements in the visible region of the input source. Prior to data acquisition, the spectrometer was calibrated to known spectral sources.

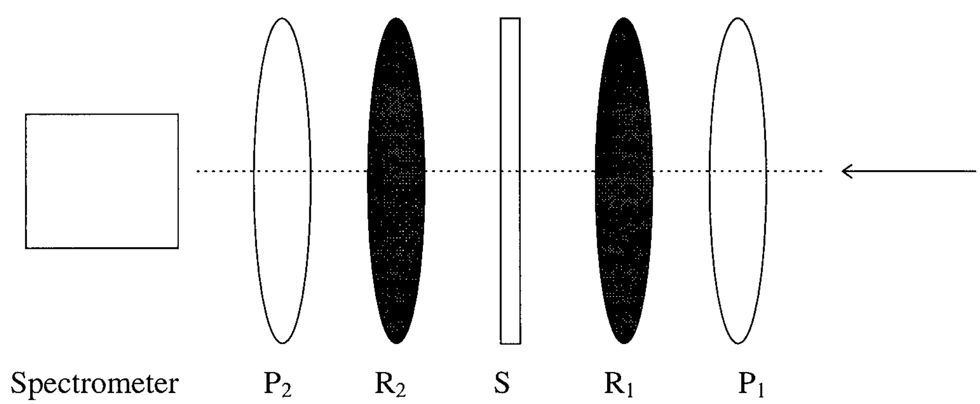

Figure 8. Experimental set-up for measurement of spectral composition at output of experiment IV.

3. Results

Figure 9 shows sample output spectra measured for a single configuration of the optical elements in the experiment. A set of such measures were taken on film samples of different optical densities, during which it became apparent that disturbances in the spectra were being captured. Sinusoidal variations in measured spectra possibly due to reflection off the film surface were observed. Hence, before any detailed analysis can be completed on the spectral properties of the film samples, this undesirable effect would need to be eliminated. This disturbance in the spectrum was minimized when the film was oriented such that the emulsion side was facing away from the source as opposed to the emulsion facing the source. We are currently attempting to isolate and reduce this effect further.

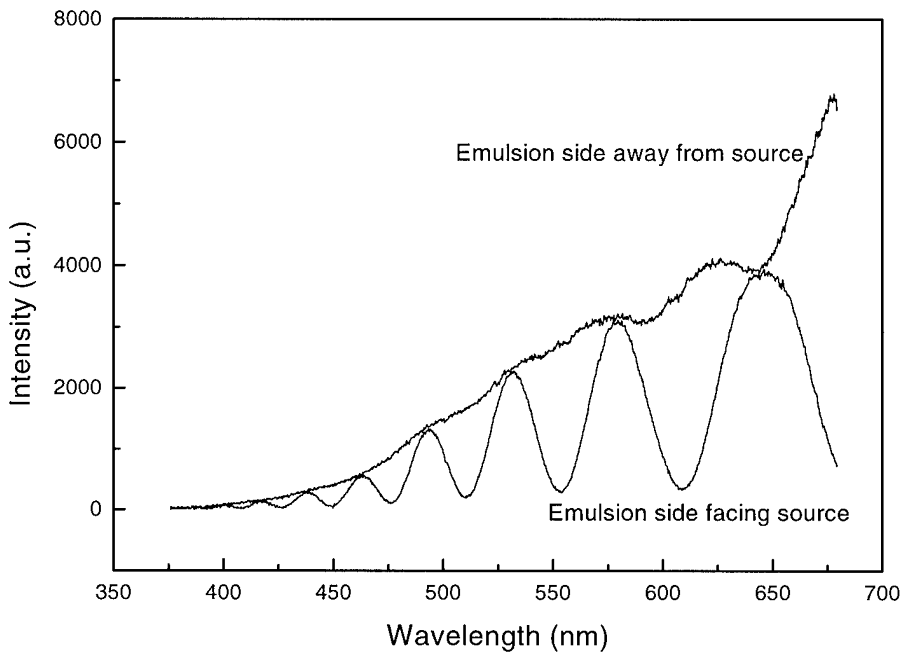

Figure 9. Output spectra from retarder R_2 for experiment V. The lower curve was intially obtained. Subsequently on reversing the film such that the emulsion side faced away from the incident source, the upper curve was obtained.

Project Summary and conclusions

This first year has concentrated primarily on laboratory set-up and on preliminary film studies. Equipment for carrying out most of the proposed experimental studies have been acquired and configured, and procedures for data analysis are currently in progress. Because the Mueller matrix will ultimately be determined for each of a set of density levels, a means of analyzing a set of such matrices needs to be developed.

As our experimental results are preliminary, it is difficult to draw conclusions regarding specific polarimetric properties which can be exploited for improved mammographic contrast. Results for the specific film brand we investigated, Eastman Kodak MinR E, seem to indicate that any potential for optically adjusting mammographic contrast will require careful consideration of the optical properties of the base material as well. This is because the film base itself demonstrated substantial polarimetric behavior. As discussed above, once the Mueller matrix is determined for both the entire film and separately for the film base, the polarimetric properties associated with the film emulsion can be isolated. It remains to be seen if the same holds true for other film brands and types. For instance, there are mammography films available that have unique (and interesting) film emulsion grain structures, and these may demonstrate substantially different and possibly exploitable polarimetric properties.

Thus far the project has fallen behind in projected progress. It was hoped to have nearly completed in the first year of the project the analysis of polarimetric properties of most all mammography films. The second year we had anticpated developing final rigorous evaluation of film candidates and a potential viewing environment which would exploit any polarimetric properties. However the project has suffered from two detrimental events. First, delay in the initiation of this project was caused by the considerable delay in obtaining the funding via inter-agency agreement procedures. We did not have access to the allocated funds until August, 1996. Hence much of the necessary equipment and supplies were not received until late 1996 or early 1997. For example, the company which supplied us with the achromatic retarders (Meadowlark Optics) had tried for months to manufacture them to quoted tolerances and apertures, but failed to do so. Hence we took delivery of a product which was of acceptable tolerances but with different apertures than we had hoped for.

Second, there has been co-investigator change-over, as two persons with primary involvement in the project have since left the agency, and it has taken considerable time to replace them. We have replaced one co-investigator, but hiring constraints may not allow for further additions to the investigation team. We do not expect this to be a problem at this time.

Nearly all equipment necessary for complete and comprehensive analysis of optical polarimetric properties of mammography films has since been acquired, and we expect to complete this aspect of the project before the end of the calendar year. In addition to determining the polarimetric properties of mammography film, we will evaluate the feasibility of developing a viewing environment which will exploit any observed polarimetric properties. The below table summarizes work yet to be completed.

	Goal	Anticipated completion deadline
1.	Completion of mammography film evaluations	12/97
2.	Experimentation and data analysis on possible practical viewing device	6/98
3.	Finalize design for proposed viewing device	8/98

One major concern is whether funding which has been allocated for FY 97 can be carried over to FY 98, as the project most likely will not have reached to the point where we could judiciously apply the funds toward support of the tasks outlined in items 2 and 3 above. As the project is being carried out by a government agency via an inter-agency agreement (IAG), strict rules regarding the allocation and utilization of FY funds are enforced. This is also being investigated.

Finally we extend our appreciation to the Department of the Army for the opportunity to carry out the proposed project. We are committed to providing a quality research product, and look forward to the successful completion of this proposal.

References

1. Azzam RMA. Photopolarimetric measurement of the Mueller matrix by Fourier analysis of a single detected signal. Optics Letters, 2(6) Optical Society of America, June 1978.